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0422-476: A shell galaxy with azimuthally distributed shells

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ABSTRACT
A morphological and two-colour CCD photometry study of the shell galaxy 0422-476, one of the richest known azimuthally distributed shell galaxies, is presented. Taking this galaxy as a prototype, a general method for reducing observational data of these objects is defined and quantitative parameters for use in further theoretical studies are derived.

According to some recent models (e.g., Thomson & Wright, 1990), the shells in such a galaxy could be density waves induced in a thick disk population of dynamically cold stars by a weak interaction with another galaxy. In 0422-476 there is no evidence of either a conventional exponential disk or a thick disk. Although it is not possible to rule out the weak interaction model, the observations continue to favour the merger model (e.g., Quinn, 1984).

Key words: galaxies: 0422-476 - galaxies: evolution mechanisms - galaxies: mergers, weak interactions - galaxies: shell galaxies - galaxies: photometry

1 INTRODUCTION

0422-476 is the best example of a shell galaxy where the shells are distributed at apparently random angles around the galaxy. In our photometric survey of the galaxies in the Malin/Carter catalogue of shell galaxies (Malin & Carter, 1984, hereafter MC) this type of system (known as Type 2) is not uncommon; roughly 30% of the shell galaxies have this structure (Wilkinson et al., 1987; Prieur, 1990). However, the shell system in 0422-476 is particularly bright and extensive, making it the ideal candidate for a detailed study of such an object. A similar study on NGC 474 has been carried out by Turnbull et al. (1999).

Several theoretical models have been able to generate randomly disposed shells. Numerical simulations (Hernquist & Quinn 1987a; Hernquist & Quinn 1987b; Dupraz & Combes 1986) of unequal mass galaxy mergers have predicted structures which are not aligned with the host galaxy major axis. Various types of perturbation of disk systems have also shown fragmentary arcs very reminiscent of those found round 0422-476 (eg, Toomre & Toomre 1972). Thomson & Wright’s numerical simulations (1990) and those of Thomson (1991) have suggested that azimuthally distributed shells could be formed by the interference of density waves produced in a thick disc population of dynamically cold stars by a weak tidal interaction with another galaxy.

Thomson (1991) used 0422-476 as an example of the sort of system produced by this mechanism. Alternative theories based on star formation in-situ (Williams & Christiansen 1985) or on dynamical instabilities of oblate systems (Merritt & Hernquist, 1991) have also been proposed.

Recently (Shiminovich et al., 1994, 1995) arcs of HI have been discovered lying parallel to but outside the outer stellar arcs in a few shell systems (Cen A, NGC 2865, NGC 474), and it would be very important to determine whether these arcs are really associated and dynamically linked with the stellar shells. The gas could have been present in a disk in the original host galaxy, or could have been added from the secondary galaxy at the time of the merger or encounter event which produced the shells. Material from extensive, weakly bound tidal tails which were formed in the encounter could still be slowly falling back into the system (Hibbard & van Gorkom, 1996).

Originally most of the shell systems were thought to be disk-less, but the discovery of gas makes it important to know whether a substantial subclass did have disks even if they were not very dominant dynamically. 0422-476 is an example of a shell system which according to Thomson’s ideas is most likely to contain a thick disk, and from its general morphology might also contain a conventional thin disk. The evidence for any disk component has been examined and the predictions of the formation theories have been compared.
with the observed properties of the system and individual shells.

2 THEORETICAL MODELS

The two currently favoured models are the merger model and the weak interaction model. Since 0422-476 appears to have little gas associated with it (see section 3), only predictions related to the stellar component will be considered, although in general it is now clear that shell galaxy models should include the possible effects of the merger of gaseous components in both the galaxies, probably on long time scales.

Shell galaxy models must explain:

(i) Where the stars that form the shells come from; the host galaxy, the intruder, or both? The shell colours, and once they are measurable, the stellar velocities, are the key pieces of evidence.

(ii) Why in about 30% of cases, the shells are symmetrically distributed about the ends of an apparently elongated galaxy (E2.5 to E5; aligned or Type I), and in another 30% they are found distributed all round a rounder galaxy (E0.5 to E3.7; azimuthally distributed or type 2)(Prieur 1990). Can these two apparently distinct types be produced by the same mechanism, or indeed do they have to be? Or is the apparent difference due simply to projection effects?

(iii) Why shells are interleaved in radius on opposite sides of the galaxy in Type 1 galaxies. In cases where they are not interleaved (Type 2 and amorphous systems), can the theory explain any observed symmetry (eg. are they symmetric about the centre or do they fit one or two-armed spirals)?

(iv) The number of shells; as many as 23 have been found for NGC 3923, though systems as rich as this are rare. Many systems only show one or two shells.

(v) The distribution problem, or the relationship between the radial positions at which shells are found. This may contain information about the galaxy potential (Quinn, 1994).

(vi) The population problem, or can the model populate shells at both large and small radii simultaneously? This question arises because of the range of radii over which shells are found; a value of \( r_{\text{max}}/r_{\text{min}} > 60 \) has been found for NGC 3923 (Prieur, 1988b), but again this is unusual. In most systems, a ratio of 10 or less would be more typical.

(vii) Pence (1986) found in NGC 3923 that the inner shells had a similar contrast relative to the underlying galaxy. This could be an indication that the shells were formed from the stars of the primary galaxy. But this property may not be general as this was not true for NGC 3051, which also formed part of Pence’s study, and Prieur (1988b) found that the two outermost shells in NGC 3923 were much more luminous than the inner ones. Clearly, further observations are needed over a much larger sample.

(viii) Shell profiles; why some shells have very sharp, asymmetric profiles, while others (sometimes in the same system) can appear diffuse? Does diffuseness imply a massive secondary, or a ‘hot’ thick disk where the shells are fragments of a spiral arm? Is it possible to distinguish between a fuzzy shell and a spiral arc?

(ix) Association with H I; this could be a way of measuring the velocities of the shell structures and may also indicate whether star formation has taken place during the shell forming process.

(x) Association with dust, if present. This may give clues as to the nature and orientation of the host potential (eg. the dust lane along the major axis in NGC 3923).

The main contenders are the merger and weak interaction models at present. How well does each satisfy the above criteria?

2.1 Merger Model

The merger model was first proposed by Schweizer (1980) and then developed by Quinn (1984). The basic idea is that during the merger and complete disruption of a small companion galaxy in the gravitational field of a larger elliptoidal galaxy, shells are density waves formed from the infalling stars of the companion. In the case of approximately radial encounters, “phase wrapping” generates a range of shells of successively decreasing radius, “interleaved” on alternating sides of the galaxy, and aligned along the direction of impact. When the impact parameter is larger, shells are formed through the process of “spatial wrapping” and they are azimuthally distributed around the main galaxy.

The type of either the primary or secondary galaxy does not preclude shell formation. Hernquist and Quinn (1988, 1989) for example, used the restricted three-body method with spherical, non-spherical and disk-like potentials for the primary. The companion was modelled by low-mass spheroids or low-mass disks. They found that (a) collisions involving low-mass spheroids, in addition to low-mass disks, can produce shells and would naturally account for the absence of gas and dust in some shell galaxies; (b) shells can be formed from companions on non-radial orbits, as well as radial orbits; (c) mass transfer that occurs during roughly parabolic encounters can also generate shells; (d) the shell morphology is sensitive to the shape of primary at large and small radii as well as to the detailed structure of the companion. This implies that it is difficult, if not impossible, to infer the form of the primary potential from the shell geometry alone.

The process is not even restricted to unequal mass mergers. Several models of major mergers (eg. Barnes 1992; Hernquist, 1992; Hibbard & Mihos, 1995) have successfully produced rich shell systems. Hernquist and Spergel (1992) produced structures which look superficially quite reminiscent of 0422-476 with a collision of two equal mass spirals.

The range of parameter space is large, but so far all models have been able to produce some sort of fine structure. The main difficulty which has emerged is that mergers cannot directly explain point (vi), the very large range in radii at which shells are found. Very tightly bound companion galaxies, or the effects of dynamical friction, must be included (eg., Dupraz & Combes 1987, Heisler & White 1990). The most detailed fully self-consistent model by Salmon, Quinn & Warren (1990) does achieve a realistic radius range, though the multiple pericentre passages of the companion’s core produce a rather complex shell system.
2.2 The weak interaction model

In the weak interaction model introduced by Thomson and Wright (1990) as an alternative to the merger model, shells are density waves in a thick disk population of dynamically cold stars generated by a weak interaction with another galaxy. Thomson (1991) modelled the thick disk using an oblate spheroidal mass distribution in which test particles are set up on short axis tube orbits with zero radial thickness. It should be emphasized that this is not what is implied by the conventional “thick disk”, which is a dynamically warm component. The initial particle distribution function is calculated so that the system is in equilibrium. The dynamically hot population of the elliptical galaxy, modelled by a Plummer potential, is supposed to be unresponsive during the encounter. The companion is set up on a parabolic orbit and also modelled by a Plummer potential. The results show that long-lived shell-like structures can be formed by this process.

Hence the presence of shells would imply that (at least some) elliptical galaxies have thick discs, and that the underlying galaxies are predominantly oblate spheroids. He suggests that the systems appear as aligned if viewed edge-on, and as azimuthally distributed if viewed face-on.

The main problem here is the necessity of introducing a hypothetical cold thick disk population of stars, contributing a few percent of the total mass.

3 PREVIOUS INFORMATION

0422-476, or ES0 202-G 015, is classified as (R')SA(rs)0+ pec in the RSA catalog (Shapley & Ames, 1932). It has an angular size of roughly 1.9 × 1.7 arcmin. The most recent photometry lists the B magnitude as 13.60 ± 0.21 (RC3, de Vaucouleurs et al., 1991). There are several small companions in our 2.63 × 4.23 arcmin field, with one small edge-on spiral lying directly in front of 0422-476 (Fig 1a).

An upper limit to the HI of less than 4.1 Jy km/sec is quoted by Huchtmeyer & Richter (1989). Van Gorkom, Schiminovich, van der Hulst, Oosterloo and Wilkinson have searched for HI in 0422-476 at the VLA (DnC array). The 5-σ mass upper limit in one 42 km/s channel is 3.2 × 10^8 M_{HI}/beam (H_0=50 km sec^{-1} Mpc^{-1}) in the field of 0422-476 itself, though HI was seen associated with ESO-202-G012, a companion galaxy some 17' away from 0422-476 with approx 350 km/s separation (private communication, Schiminovich).

The Uppsala Catalogue gives (B_T - R_T) = 1.36 (Lauberts & Valentijn, 1989). The heliocentric velocity is 4270 ± 31 km sec^{-1} (Carter et al., 1988), or 4320 ± 14 km sec^{-1} according to the RC3 catalogue. The first value gives a distance of D=85.4 Mpc, taking H_0 = 50 km sec^{-1} Mpc^{-1}. The spectrum is that of a typical elliptical galaxy, showing Ca H and K absorption, Mg b and the G band, and no obvious emission. No A star contribution was detected (Carter et al., 1988). The central velocity dispersion is 169 ± 76 km sec^{-1} (see also McElroy, 1995).

Using the version of the Faber-Jackson relation (Faber & Jackson, 1976) as calibrated by de Vaucouleurs and Olsen (1982) yields: M_B^T = -18.75.

Assuming the simplest isothermal sphere model, the mass M ∼ 2σ^2r/G is 2.92 × 10^{11} M_⊙ within 53' (ie. the radius of the outermost shell).

4 DATA

Four CCD frames in both R and B filters were obtained at the prime focus of the 3.9 metre Anglo-Australian Telescope in January 1986 (Fig 1a). The seeing was 1.0 arcsec, and the conditions photometric. The scale was 0.492 arcsec/pixel, and the field was 2.6 × 4.2 arcmin. Exposure times were 60 and 500 seconds in the blue, and 60 and 300 seconds in the red filters. Standard frame reduction techniques (de-biasing, flat-fielding, defringing and removal of cosmic rays) were employed.

Stars were removed from the blue and red frames, and the sky level was determined from an average in all four corners of the frame. The Sky Survey image indicates that there is not likely to be any significant structure outside the frame (Fig 1e). The background was fitted with a first order polynomial and the resulting rms error in the final photometry was ± 0.03 mag/pixel. The presence of a bright star just outside the frame to the west precludes making quantitative comments about shells in that quadrant.

Standard star field frames were taken at regular intervals to determine the atmospheric absorption and allow calibration of the photometry. As the filters were not the conventional Johnson filters, colour corrections were necessary and were calibrated with standard photometric stars.

An additional set of CCD frames was taken at the 40-inch telescope of Siding Spring Observatory in December 1987 with a larger field 3.6×5.3 arcmin (0.56'/pixel). As these files were originally on half-inch tapes in the old Starlink BDF format, we have written a conversion program to FITS format to allow for processing on Unix systems.

5 THE GALAXY

The shells are so bright that they distort the isophotes at almost all radii, especially in the outer parts where the shells become predominant (Fig 1a). The study of the morphology and photometry of the galaxy is thus hindered by the shells.

5.1 Galaxy isophotal parameters and galaxy subtraction

Ellipses have been fitted to the isophotes of the galaxy, looking for a possible signature of the presence of a disk (as a simultaneous change of some of the isophotal parameters could be a hint of the presence of a disk in elliptical galaxies, cf. i.e., Bender, 1988).

At small radii, the presence of bright shells induces a large variation of ellipticity and position angle. We then note a small increase of about 20 degrees of the position angle occurring at a radius of about 35 arcsec, which seems linked to a decrease of ellipticity (hence an increase of the uncertainty of the position angle). But these variations must be due to the presence of the bright shells S05 and S06 which nearly fully surround the galaxy. At larger radius, the behaviour of the isophotal parameters is consistent with a “featureless
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Figure 1. 0422-476. From left to right and top to bottom: (a) AAT CCD R frame before processing. (b) galaxy subtracted from (a) with a mean profile and ellipses with free parameters. (c) galaxy subtracted from (a) with a minimum profile and ellipses with fixed parameters. (d) radial gradient of (a). (e) ESO/SSO Sky Survey E print image, showing no structure beyond shell S01. (f) 40″-SSO R CCD frame.

elliptical" and does not give any indication of the presence of a disk.

Likewise, the Fourier B4 parameter does not differ significantly from zero at any radius, showing no particular 'boxiness' or 'diskiness'.

5.2 Galaxy subtraction

The background light of the galaxy had to be removed to study the morphology and the photometry of the shells. If shells are envisaged as formed from material which originally came from a second galaxy, they may be regarded as having been added on to the original primary galaxy profile. Profiles computed along elliptical annuli in each of twelve 30 degree sectors showed significant variations from sector to sector. To approximate as closely as possible the 'bare' primary galaxy, a minimum profile was constructed using the minimum sector value at each radius. This assumes that there is always at least one sector where there are no shells present, which is not self-evidently true, but represents the best approximation possible. Although the concept seemed attractive, only subtle qualitative differences could be seen when comparing minimum and mean profiles.

Both mean and minimum profiles were used to construct models of the underlying galaxy using the Bmodel task in the STSDAS package in IRAF. It was necessary to fit the nuclear region within 15 arcsec separately, letting the centre vary freely, while for the outer regions a fixed centre
was adequate. In order to ensure a smooth subtraction of the outermost parts of the galaxy, where the galaxy contribution is below the sky level, the profile used by $B_{model}$ was extrapolated following the fitted $r^{1/4}$ law. This avoided introducing any artificial shell-like structures at large radii, and displayed the shells to best advantage. Fig. 1b shows the subtraction of a mean profile from the red frame.

However, there was concern that the shells could still be affecting these galaxy models. Since the parameters were fitted locally, the galaxy subtraction might have reduced the intrinsic brightness of the shells, by assuming an artificial increase of the background brightness of the galaxy at the location of the shells. Spurious ellipticity variations could also have been introduced.

To circumvent these difficulties, a different approach was also used. A simpler elliptical model for the galaxy with a fixed centre and ellipticity, and a minimum profile, was subtracted. Fig. 1c shows the result on the red frame. The residual background is larger than with the free-ellipticity model, in the center region, since small variations of ellipticity in the center induce big variations of brightness. But this simpler model has the advantage of being locally unaffected by the presence of shells and hence should not reduce the shell luminosities. It was preferentially used for measurements of the shell photometry.

### 5.3 Luminosity Profile

The mean red and blue luminosity profiles are well fitted by the de Vaucouleurs $r^{1/4}$ law (Fig. 2). A brightness enhancement is only seen in the frame (at a radius less than 4 arcsec) and in the extreme outer edge where the profile is dominated by the outermost shell. There is no evidence for the presence of a conventional exponential disk component, or any other extended component. Another set of “minimum” $B$ and $R$ profiles (as defined in §5.2) which reduced the contribution of the shells, have been computed but did not show any qualitative change from the mean profiles, except that they were more noisy.

The fitted equivalent radius and magnitude are:

- $r_e = 20.6 \pm 1.0$ arcsec and $B_e = 22.1 \pm 0.5$ in the red and $r_e = 23.6 \pm 1.0$ arcsec and $B_e = 23.9 \pm 0.5$ in the blue for a fit between a radius of 2 arcsec and 80 arcsec, and the scatter is 0.09 magnitude rms.

A search was made for a signature of the thick disk in the form of an additional St"ackel component as used by Thomson (1991) in the luminosity profile. The projected St"ackel density profile falls off more rapidly than the de Vaucouleurs law, which meant any St"ackel component had to have a very large scale compared with the fitted de Vaucouleurs law, appearing more like a halo than a part of the visible galaxy. This was not consistent with the St"ackel model as used by Thomson (1991). No significant improvement in the fit was obtained, and so it was concluded that there is no additional thick disk component. This does not preclude there being a short axis tube population within the ellipsoidal galaxy mass distribution already modelled by the $r^{1/4}$ law (see Sec. 11.3), so long as it does not dominate the mass distribution.

### 5.4 Colours and colour gradient.

Fig. 7 shows the $B-R$ colour profile for the underlying galaxy. The galaxy is redder at the centre and becomes slightly bluer with increasing radius. The $B-R$ range is consistent with a normal $T=-5$ elliptical or even redder (Buta and Williams, 1995). The colour gradient is $\Delta(B-R)/\log r \sim -0.18$ magnitudes per decade, which is compatible with what is found for normal ellipticals: $\Delta(B-R)/\log r \sim -0.1$ magnitudes per decade (Franx, 1988).

The very centre is much redder (Fig. 7). This could be due to the presence of dust, which could be the remnants of the gas of the companion galaxy, in the merger hypothesis, although no clear “dust lane” structure can be seen in the center of the $(B-R)$ image.

### 5.5 Magnitude determination

The curve of growth was determined by summing the corrected intensity in the $B$ frame in magnitudes per square arcsecond within circular apertures of increasing radius, from 2.5 arcsec out to 47.5 arcsec, and fitted to the standard galaxy luminosity curves (curves of growth) given by de Vaucouleurs (1977) for galaxies of type $T=-1$ to $-5$ (see RC2 for $T$ type definition). The $T=-5$ curve gave the best fit, giving no hint that 0422-476 is anything but a typical elliptical galaxy. There is no suggestion of a disk, but the fit is not good at radii less than about 11.9 arcsec (which is due to the brightness enhancement seen in Fig. 2). The best fit was for $B^2_e=13.37 \pm 0.03$, which is slightly smaller than the value of 13.60±0.21 given in (RC3, de Vaucouleurs et al., 1991). The effective aperture, or the diameter of the circular aperture which contains half the total $B$ light of the galaxy, was found as $A_e = 43.1 \pm 2$ arcsec.
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6 GEOMETRY OF THE SHELL SYSTEM

For morphological studies, the long red and blue exposures of the AAT were added to maximise the signal to noise. The shell outlines were determined by hand from the direct image and the image with the mean galaxy subtracted (cf. §5.2). RL, AW and JLP determined sequences of points on the shell edges independently, and the scatter between the three sets of data gives an estimate of the reliability with which the shell edges could be determined (typically about 2.5 arcsec). This reflects both the fact that some arcs are not sharp and the scatter of independent determinations.

It was possible to display the shells without galaxy subtraction over a considerable brightness range by taking the radial gradient transformation of the logarithm of the image (Fig. 1d). This worked well at all radii and in particular picked out detailed structure close to the nucleus. But, as this processing may have shifted the shell edge slightly, we used this gradient filtered image used for confirmation only.

The outermost shell was measured on the sum of the images taken at the 40-inch telescope of Siding Spring Observatory (cf. § 4, and Fig 1f), since the field of view was larger. Fifteen shell arcs were distinguishable (see Fig. 3), the arcs are concentric and do not intersect one another. The shells were numbered from the outermost to the innermost. The edge of the outermost shell S01 is not sharp. As it is faint, this may not be intrinsic but simply due to a poor SNR. Generally, the outer shells have a sharp edge whereas close to the center, the shells have a more diffuse appearance, and it is more difficult to determine which arcs are associated. This was also noted for NGC 3923 (Prieur, 1988b), in the inner parts, where the shell profiles were more symmetric than those of the outer parts.

Ellipses were then fitted to the shell arcs. The shell arcs are consistent with fragments of ellipses whose centers are very close to that of the galaxy. Except for shell S04, satisfactory fits were obtained with a centre fixed at the centre of the galaxy. For S04, it was best fitted by a slightly shifted centre (offset: 3.1±4 arcsec West, 2.5±2 arcsec South). The ellipticity of the shells lies in the range 0.4 to 2.8, with a mean of 1.8±0.9. This is comparable with the mean ellipticity 1.6±0.7 of the galaxy isophotes over a similar radius range.

Fig. 4 shows all the shell outlines plotted in polar coordinates. In this plot, elliptical shells confined to a fairly narrow section about a plane should show a sinusoidal variation about constant radius, and truly circular shells would be vertical straight lines. No clear spiral structure can be seen in the inner 20 arcsec. In general there is no systematic evidence for spiral structures in 0422-476. The only shell fragments which could be interpreted as indicating a spiral nature (as predicted by the weak interaction model) are S03 and the southern part of S04, though the northern part of S04 does not continue this trend (cf. Fig 4b). These arcs have been fitted to a linear Archimedean spiral r = aθ and to a logarithmic spiral r = exp(aθ). The fit is slightly better with a logarithmic spiral but the difference is not significant. The pitch angle measured on the fit with the logarithmic spiral of S03-S04 is i = 7.7° (cot(i) = 7.44 ± 0.09) whereas the pitch angle of the southern part of S04 is i = 4.6° (cot(i) = 12.55 ± 0.11).

7 SHELL SPACING AND INTERLEAVING

7.1 Radius range

In the case of 0422-476, the radius range over which shells are produced is by no means as extreme as in the case of NGC 3923; here rmax/rmin ~ 12 rather than 62 for NGC 3923 (Prieur, 1988b). 0422-476 therefore presents less of a challenge to the merger model, as it is possible to explain such a radius range simply by having a fairly tightly bound nuclear component in the companion. Apart from...
NGC 3923, the ranges found by Prieur (1988a) for aligned systems vary between 4 and 13, and so in this respect there appears to be little difference between aligned and azimuthally distributed systems. The radius ratio in Thomson’s (1991) model appears to be between 10 and 20.

7.2 Interleaving

The merger theory predicts that the shells located in opposite sectors should interleave in radius in aligned systems (Quinn 1984). Interleaving is not predicted for azimuthally distributed shells, but as one cannot exclude a priori that such systems are aligned systems seen face on and to be able to compare with some predictions of theoretical models (eg. Thomson 1991), this notion is extended to all systems in the following way: the radius $a_\alpha$ of the intersection of the shells with the major axis of the galaxy are measured and plotted in two columns according to the sector where the shells lie (following Fig. 10 of Prieur (1988b), for the aligned system of NGC 3923). No clear interleaving can be seen in this diagram (Fig. 5a), nor any symmetry observed in the central region as it was observed for NGC 3923 (Prieur, 1988b).

7.3 Radius ratios

For 0422-476, Fig. 5b shows that the ratio of the radii of successive shells in the same sector (Northern or Southern) is rather constant with a mean value of $\sim 1.35 \pm 0.1$. This was already found by (Prieur, 1988b), who found 1.3 for NGC 3923. Hence systems as different as NGC 3923 and 0422-476 exhibit a similar distance ratio. The question whether this is a constant for all shell systems needs further investigation.

The weak interaction theory predicted such a regular spacing for the successive shells since they belonged to spiral arcs. In the merger hypothesis, Quinn (1984) gives predictions of the radial distribution of shells in aligned systems governed by “phase wrapping”, but no clear prediction of a constant radius ratio in the case of “spatial wrapping” for systems like 0422-476.

Thomson (1991) predicts a shell spacing of $\alpha = 1 + (\pi / \cot i)$, where $i$ is the pitch angle of the spiral. The logarithmic spiral fitted to the fragments S03 and S04 gives $i = 7.7^\circ$ (cf. §6), and thus predicts a successive shell radius ratio of $\alpha = 1.42$, whereas the fit with the southern part of S04 ($i = 4.6^\circ$) would lead to $\alpha = 1.25$. These values are then compatible with our measurements. But it should be recalled that these two “spiral-like” shells are the only shells that we found among the 15 shells of the system which globally do not show a spiral structure as expected by Thomson’s model (Fig. 4).

8 SHELL COLOURS

The determination of the shell colour indices were difficult due to the low contrast of the shells, and the B and R images had to be processed in exactly the same way.

To increase the signal to noise ratio, the individual shell colours of the dominant shells were calculated from the mean profiles averaged over angular sectors displayed in Fig. 6 using the geometrical parameters of the shells. Various sets of profiles with different parameters were used to test the robustness and estimate the errors. When possible (for the outer shells f.i.), colours were measured on the original images but most of the time it was necessary to work on the images where the main contribution of the galaxy had been removed as explained in § 5.2. Even in that case, it was still necessary to fit a residual baseline for the shell profile, as illustrated in Fig. 10. This fit was done after displaying the B and R profiles in the same graph in order to select a similar baseline for both colours and check that both profiles had a similar aspect (which was the indication of a correct subtraction of the galaxy in both colours). Several different baselines were used to reduce (and estimate) the errors. The profiles were then integrated over the azimuthal range covered by the shell to derive the total luminosity of the shell in each colour.

A synthetic “color map” of the shells is shown in Fig. 6: no special trend, either radial or azimuthal, seem to exist. One could be puzzled by seeing that colour differences can be seen along some shells (eg. for S03 and S07). This effect is believed to be real and larger than the measurement errors. It was also visible when directly dividing the B and R raw images. Such a colour scatter could indicate that the material making up a given shell has different origins. This could be explained in the merger hypothesis since the shells are formed from stars with similar dynamical parameters relative to the host galaxy (i.e. same apocenter), but would be more difficult to interpret in the case of an internal origin where one expect a similar stellar population (Thomson’s model or in the case of induced star formation, Williams and Christiansen, 1985). Numerical simulations of mergers of a spiral galaxy with bulge and disk can easily produce tangential colour gradients within the shells (see f.i., Prieur, 1988a).

Compared to the galaxy colour difference (B−R) profile determined from the mean profiles, the shell colours are scattered about the underlying galaxy value (Fig 7). No significant shell color radial gradient can be noticed.
Figure 6. Angular sectors where the B–R colours of the shells have been measured. The B–R indices are displayed on the gray scale given on the left (the average B–R index of the galaxy is 1.4).

Figure 7. Shell colours of 0422-476. B–R colour indices of the main shells (black squares) compared to that of the underlying galaxy (solid line).

9 SHELL SURFACE BRIGHTNESS AND LUMINOSITY

The constancy of shell surface brightness as a ratio of the underlying brightness has been quoted as an important parameter by Thomson (1991), but as seen in §2, this is not very well established by observations since it was only observed for the very inner shells of NGC 3923 (Pence, 1986).

Fig. 8 shows that for 0422-476, the surface brightness of the shells decreases as the radius increases, but with a smaller slope than that of the galaxy itself. This implies that the contrast of the shells relative to the galaxy increases in the outer parts. This is comparable with the surface brightness distribution found for shells produced in major mergers (Hernquist & Spergel, 1992). The fact that in many systems shells are more easily detectable at large radii suggests that this is true for most shell galaxies.

The total luminosity for each shell was obtained by adding the luminosities of the sectors for that shell and plotting the resulting numbers in Fig 9. The error of the total luminosity of the outermost shell S01 in Fig. 9 maybe overestimated, but we conservatively assumed a big uncertainty of the total angular extension of the shell, which was only measured on the SSO frames of poorer quality than the AAT frames.

Although the surface brightness increases as the radius decreases, the total luminosity is roughly constant with the radius. This differs from NGC 3923, where the two outermost shells are dominant in terms of luminosity (Prieur, 1988b).

To measure the total luminosity of the shells, a set of 30-degree profiles was computed covering the whole CCD frame from the AAT and the total luminosity above a fitted background was derived for each shell. For the outermost shell S01 which was not visible on the AAT frames, we derived a value by taking into account the angular extension measured on the SSO frames (Fig 1f), since its surface brightness was rather uniform along the azimuthal direction. We then derived a total magnitude of the shells of $B_{\text{shells}} = 16.77 \pm 0.2$.

This value corresponds to 4.4%±0.8% of the total B magnitude of the galaxy (cf., § 5.5, $B_T(\text{galaxy})=13.37$). The uncertainties come mainly from the removal of the background of the galaxy. Hence the relative luminosity of the shells is rather small compared to the measurements already made on other bright shell galaxies: 16%±6 for NGC 2865, 14%±5 for NGC 3018 Fort et al., 1986. But it is similar to
Table 1. Parameters of the 3-D model fitted to the shell profiles:

<table>
<thead>
<tr>
<th>Shell Number</th>
<th>$r_s$</th>
<th>$r_g$</th>
<th>$\Phi$</th>
<th>$\rho_0$</th>
<th>Relative thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>104.0</td>
<td>6.0</td>
<td>50</td>
<td>1.50</td>
<td>5.7%</td>
</tr>
<tr>
<td>S02a</td>
<td>69.0</td>
<td>1.3</td>
<td>28</td>
<td>0.38</td>
<td>1.9%</td>
</tr>
<tr>
<td>S03</td>
<td>64.6</td>
<td>1.4</td>
<td>34</td>
<td>0.75</td>
<td>2.2%</td>
</tr>
<tr>
<td>S05b</td>
<td>40.2</td>
<td>1.3</td>
<td>27</td>
<td>1.35</td>
<td>3.2%</td>
</tr>
<tr>
<td>S06a</td>
<td>32.0</td>
<td>2.0</td>
<td>37</td>
<td>2.10</td>
<td>6.3%</td>
</tr>
<tr>
<td>S07</td>
<td>32.1</td>
<td>1.8</td>
<td>42</td>
<td>3.60</td>
<td>5.6%</td>
</tr>
<tr>
<td>S07c</td>
<td>33.2</td>
<td>2.0</td>
<td>40</td>
<td>2.95</td>
<td>6.0%</td>
</tr>
<tr>
<td>S07e</td>
<td>26.0</td>
<td>1.5</td>
<td>45</td>
<td>3.50</td>
<td>5.8%</td>
</tr>
</tbody>
</table>

The values found for NGC 3923: 5%±3 (Fort et al., 1986) and 4.5%±1 (Prieur, 1988b).

10 SHELL PROFILES

The radial profiles of the integrated shells were fitted with a 3-D model which assumes that the shells are spherical surfaces with a radial Gaussian distribution of stars:

$$\rho(r) = \rho_0 \exp\left(-\frac{(r - r_s)^2}{r_g^2}\right)$$

The center of the shells was taken at the center of the galaxy and a constant azimuthal density was assumed over the angular extent $2\Phi$ (along the line of sight). The resulting profile was broadened by the atmospheric seeing. The fits were very good as shown in Fig 10 for most of the shells. For the innermost shells, as the shape of the profiles was strongly dependent on the way the background of the galaxy had been removed, no model fitting has been attempted.

The fit parameters (Table 1) are rather homogeneous and do not exhibit any special trend with the shell distance to the center of the galaxy.

The thickness of the outermost shell S01 is significantly larger than the others: 6° instead of the average value of $< r_g > = 1.6° ± 0.3°$ for the other shells of Table 1, but it is only due to its large radius: its relative thickness $r_g/r_s$ (column #6 of Table 1) is similar to that of the other inner shells. Taking into account an estimated distance of 85 Mpc (Cl., § 3), the average thickness of the inner shells is $< r_g > = 0.66 ± 0.12$ kpc. The mean half-angular extent is $< \Phi > = 38° ± 8°$. It is comparable to the mean value of the half angular extent in the plane of the sky $< \Delta \Theta/2 > = 44° ± 15°$ obtained for the same shells (S01, S02, S03, S05, S06 and S07). Hence the angular extent of the shell in the plane of the sky ($\Delta \Theta$) and in the perpendicular direction ($2\Phi$) are similar: the 3-D shape of the shells seems to be a portion of a sphere with an angular extent of about 80 degrees. They are not flat but real 3-D structures.

As the shape of the shells follows the equipotentials of the gravitational field (see eg., Prieur, 1988a), this gives an indication that 0422-476 is not a flat oblate system seen face on.

11 DISCUSSION

The shell system in 0422-476 was very rich and rather bright, which has allowed accurate measurements to be made for

![Figure 10](image_url)

the first time on this type of galaxy. It originally attracted attention as the clearest example of a Type 2 galaxy, and is a good object against which to test the predictions of the various shell galaxy formation models.

11.1 0422-476 as a prototype of azimuthally distributed shell systems

In fact, 0422-476 is probably as atypical of the azimuthally distributed systems as NGC 3923 is of the aligned systems, in that both have such unusually rich and extensive shell systems. It may not be surprising if it is necessary to invoke somewhat special impact parameters, orientations or stellar populations to explain these objects. A whole range of merger or interaction situations can produce shells, with the richest examples of the class defining the limit for a satisfactory model.

11.2 Comparison of axial and azimuthal systems

A basic tenet of the weak interaction hypothesis is that the Type 1 and Type 2 galaxies are oblate systems viewed either edge on or pole on. A Type 1/Type 2 comparison can be made, taking NGC 3923 as the prototype of the Type 1 galaxy. Turnbull et al. (1999) have provided further information on a Type 2 system in their study of NGC 474, albeit a more complex case because of its kinematically distinct core and companion NGC 470, and on a Type 1 system in NGC 7600.
The most important observed feature of Type 1 is the interleaving of the shells along the host galaxy major axis, which ought to be observable in both systems if the only difference is orientation. The one and two armed spirals predicted by the weak interaction mechanism ought also to lead to regular interleaving along a given axis. No clear interleaving could be observed along the major axis of 0422-476, but when numbering the shells according to their radius, a rather constant distance ratio of 1.3 between two successive shells was found, as in the case of NGC 3923. On this point, the results remain inconclusive.

NGC 3923 and 0422-476 show relatively simple patterns, with concentric shells (without shells intersecting one another) suggesting there have not been multiple passages of a secondary galaxy nucleus, and there is no (obvious) subsidiary nucleus. Secondary nuclei are very rarely found even in well established mergers, so this is not necessarily evidence against a merger origin.

In 0422-476, the surface brightness of the shells decreases less rapidly than that of the galaxy, but the total luminosity of each shell is roughly constant with radius, which could be consistent with material being added from outside. For NGC 474 and NGC 7600, the surface brightness is roughly constant with radius, and Turnbull et al. (1999) regard the fact that it does not follow that of the galaxy as a strong argument against the weak interaction model.

In all the galaxies, the colours of the shells are roughly similar to the colour of the main galaxy with a large scatter. In 0422-476 there are real colour differences between the shells and within the shells up to 0.3 magnitude, with no special trend with radius. This could support the weak interaction theory, insofar as the shell systems could be created from the primary galaxy material in all cases. However, it does not preclude the merger theory if the companion were of a similar type to the primary. The color scatter within some shells (cf. §8) is a more serious problem for the weak interaction model where the stars within the hot disk should be mixed and form a homogeneous population.

The outer shells in both NGC 3923 and 0422-476 are sharp-edged and are well fitted by a model of a Gaussian 3-D shell. The good fit to a spherical Gaussian shell indicates a true 3-D structure with an angular extent along the line of sight of the same order as that in the plane of the sky. This suggests that 0422-476 is not a strongly oblate system seen face on, since the shape of the shells follows the equipotentials of the gravitational field. This may contradict the basic hypothesis of Thomson’s model that the shells are formed in oblate potentials. The large angular extension of the shells of about 80 degrees along the line of sight may be difficult to reconcile with the hypothesis of a “thick disk”.

In the inner part of 0422-476 the shells become more diffuse and have a symmetrical gaussian radial profile, reminiscent of the radial section profiles of spiral arms (e.g. Seigar & James, 1998). NGC 3923 also shows symmetric shell profiles in the inner shells. This is what would be expected under the weak interaction mechanism. The changeover occurs at around 20 arcsec (about Rc), which according to the weak interaction formalism, would indicate the pericentre of the companion’s passage.

Neither NGC 3923 nor 0422-476 have detectable HI associated with them. Presumably none of the interacting galaxies were gas-rich before the events.

### 11.3 Presence of a cold “thick disk”?

The lack of detectable thick disk may not necessarily rule out the weak interaction picture. Most triaxial and oblate spheroidal galaxies contain a percentage of short axis tube orbits (Statler, 1987). This population would be unlikely to be dynamically cold, and would not usually be described as a thick disk. Statler found from 20% to 60% (maximally rotating case) of the mass of his oblate spheroidal models in these short axis tube orbits, depending on the angular momentum in the system. These stars may respond preferentially to major perturbation during an encounter. But it is unrealistic not to include the response of the remainder of the host galaxy orbits and the large fraction of the stars which will be stripped from the interloping galaxy in such an intimate encounter. If some sizeable fraction of the short axis tube orbit population is cold enough to qualify as Thomson’s “cold thick disk”, then self-consistent models may have already been run, under the guise of the conventional merger models. The Thomson’s model is probably already contained within the much more general set of possible mergers. However, in these cases the observable effects have been found to be mainly a result of the stars lost from the companion galaxy.

In the case of 0422-476 it seems that the mass of the cold disk required may be significantly larger than 20% to 50%. As the shells are density waves of stars in that disk, a lower estimate of the ratio of the luminosity of the disk to that of the galaxy, L_{disk}/L_{shell}, is given by the ratio of the total luminosity of the shells to that of the galaxy. L_{shells}. In §10 it was shown that observationally L_{shells} is of the order of 5%.

In Thomson’s model, with an estimate of 10% of the total luminosity of the disk visible under the appearance of shells (cf. Fig. 4 of Thomson & Wright, 1990), the “thick disk” would have a luminosity of about 50% of that of the whole galaxy, which should have been detected on the profiles (cf. § 5.3). Such a substantial Stäckel component should have made the luminosity profile fall off as r^{-4} (de Zeeuw, 1985), which is clearly not the case except perhaps in the very outer parts, where the background subtraction is sufficiently uncertain that no firm conclusions can be drawn. If the thick disk component does comprise 50% of the luminosity, then the secondary galaxy would be comparable in mass to the primary.

Mergers are more efficient at converting the luminosity of the companion into shell luminosity than the weak interaction model (Cf. §5.2). The efficiency η_{shells} is around 50% for young systems (from the diagrams of Dupraz, 1984, Hernquist & Quinn, 1988) but this decreases as the number of shells increases, since the shells overlap and contribute to a diffuse background of increasing brightness. For 0422-476, the large number of shells implies that this system is rather old (i.e., many crossing times for the innermost shells) and the “relative efficiency” in making shells from the original material of the infalling galaxy (cf. §2.1) must be rather low, below 20%. If less than 1/5th of the stars contributed by the companion galaxy are visible in the shells, the secondary is likely to have contributed more than 25% to the total luminosity of 0422-476. Most of the early merger simulations (Dupraz & Combes, 1986, Hernquist & Quinn, 1988) assumed that the ratio m_{comp} of the mass of the companion
to that of the host galaxy is small, of the order of a few percent only, but some full N-body simulations with higher values of $m_{\text{comp}}$ have also led to shell formation. In that case, the shells formed tend to be less well-defined since the number of stars each contains is lower due to computational limitations (eg. Hernquist and Quinn 1989).

Bender (see Bender (1998) for a summary) has shown that many ellipticals are now known to have disky components, and these tend to be lower luminosity galaxies than 0422-476, where the disk contributes from a few to 30% of the light. These galaxies are rotationally supported, with dissipation and gas dominating during their evolution. Easily recognised major merger remnants tend to be triaxial, anisotropic, slow rotators, with peculiar velocity fields and nuclear cores. If shell galaxies are merger products, and as indicated above, perhaps the result of rather more major mergers than previously expected, the lack of any detectable disk in 0422-476 may therefore not be too surprising.

The ultimate test of the weak interaction theory is the measurement of the velocities of the stars forming the shells (eg. Balcells & Carter 1993; Merrifield & Kuijken, 1998), as pointed out by Thomson & Wright (1990). Such measurements will be achievable by the next generation of instruments, but another spectroscopic test may already be available. A galaxy composed mainly of zero-thickness short axis tube orbits would be likely to be rapidly rotating, with an apparent velocity characteristic of the stars in their orbits. A detailed major axis rotation curve of this galaxy, although it cannot be very highly inclined, might display such an effect even if it were unable to yield details of the velocities in the shells themselves. Bender’s correlation leads us to predict that since 0422-476 shows no sign of a disk, it will be found to be slowly rotating.

11.4 Weak Interaction versus Merger models

The implications of the 0422-476 results for each of the main models can be summarised as follows. The main results which support the weak interaction model are:

(i) The possible spiral pattern in shells S03 and S04. This could be part of a one-armed leading outer spiral.

(ii) The symmetric radial profile of the inner shells which resembles the cross section of spiral arms.

(iii) The change in shell structure at a specific radius.

(iv) The ratio of successive shell radii (§7.3).

Here are the main results which contradict the weak interaction model:

(i) The diffuse inner shells do not show any global spiral structure neither exhibit any bisymmetric pattern (Fig 5). There is not any general one armed spiral in the outer shells (§6).

(ii) The shells are not interleaved along the major axis (§7.2).

(iii) In the case of the only possible spiral pattern seen in shells S03 and S04, the profiles are sharp-edged and do not look like the radial spiral arm profiles. It seems unlikely they are normal spiral arms. On the contrary, the apparent spiral could well be a result of partial spatial wrapping with sharp-edged profiles (Quinn, 1984).

(iv) The intrinsic colour dispersion of the shells is greater than would be expected of shells arising from a cold disk population, and there exist a large dispersion within some of the shells (§8.1).

(v) The surface brightness of the shells does not follow the surface brightness of the galaxy (§9).

(vi) The potential may be not oblate, as shown by the fit of the shell profiles, and the shells have a large angular extension in 3-D (§10).

Hence 0422-476 shows features which favour both models, but there are some contradictions with the weak interaction model. It is possible that elements of both mechanisms could have been at work. The outer shells could have been formed of the stars of a cold, low-dispersion companion disk galaxy, and the inner shells could be due to the perturbation of the host galaxy. Alternatively the interloper could have had a relatively hot nuclear bulge which was responsible for the inner shells.

12 CONCLUSION

0422-476 is the richest azimuthally distributed shell galaxy to be studied in detail and searched for any evidence of a conventional or thick disk component. There is no sign of an exponential disk, or any thick disk additional to the short axis tube orbits already expected within an oblate ellipsoidal potential. Although the inner structures may reflect the response of a population of short axis tubes, the overall shell system and the structure of the outer shells are consistent with those predicted by the merger model. The balance of evidence suggests that the merger model, in all its variety, can explain both azimuthal and aligned shell systems.

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